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RESULTS OF FURTHER METALLURGICAL INVESTIGATIONS OF STEAM GENERATOR TUBE FAILURES AT BRUCE A

Report No. 86-194-K

B Warr, Engineer
Corrosion and Tritium Technology Section,
Metallurgical Research Department.

ABSTRACT

Several tube leaks have occurred in the large radius U-bend region of the Bruce A steam generators. It has been proposed that a synergistic stress corrosion cracking/fatigue mechanism is responsible for these failures. In order to assess the extent of damage in tubes that have not failed, a sacrificial tube has been examined using Scanning and Transmission Electron Microscopy, and compared with results from tubes which were fatigue tested in the laboratory. Dislocation densities were found to be significantly higher just beneath the upper land region of the sacrificial tube, the same location where cracks have been found in leaking tubes. This increased dislocation density may be early fatigue damage resulting from cyclic stresses during operation. The results are tentative, however, and further examinations of sacrificial tubes, which may be removed in the future, are required to confirm them. Stresses required for crack initiation in Inconel 600 are compared with estimated tube stresses present in the Bruce A steam generators. Recommendations are made for further work.

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EXECUTIVE SUMMARY

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Several tube leaks have occurred in the large radius U-bend region of the Bruce A steam generators. It has been proposed that a synergistic stress corrosion cracking/fatigue mechanism is responsible for these failures. In order to assess the extent of damage in tubes that have not failed, a sacrificial tube (#55-10) removed from Bruce Unit 3, steam generator 7, has been examined using Scanning and Transmission Electron Microscopy. Samples of I600 tubes which were fatigue tested in the laboratory were also examined for comparative purposes. Dislocation densities were found to be significantly higher just beneath the upper land region of the sacrificial tube, when compared to other locations in the same tube. This is the location where cracks had previously been found on leaking tubes. A similar increase in dislocation density was observed in a sample of tubing which had been fatigue tested in the laboratory. A possible explanation of the increased dislocation density in the sacrificial tube is the presence of alternating stresses during operation. However, this evidence is at present tentative since the work is difficult and only one sample has been examined. It is not possible to determine the extent of the damage, ie when and if crack initiation will occur. Maximum alternating stress amplitudes of 90 MPa have been estimated for tubes in the critical region, approaching the fatigue threshold for the tubing material of 117 MPa in saturated steam.

Modifications made to the Bruce A steam generators may have lowered the stress amplitudes of tubes in the critical U-bend region of the inner steam generators, and hence may account for the recent lack of tube failures. In the event that further leaks occur in the upper U-bend region of Bruce A steam generators, sacrificial tubes containing the portion of the tube within the top horizontal support plate should be removed together with any leaking tubes, for further examination. Further work is planned to determine tube stresses and vibrational behaviour in-situ. A program of limited fatigue tests is recommended, and it is suggested that some consideration should be given to developing practical in-situ remedial measures to decrease the failure rate should further tube leaks occur.

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RESULTS OF FURTHER METALLURGICAL INVESTIGATIONS
OF STEAM GENERATOR TUBE FAILURES AT BRUCE A

1.0 INTRODUCTION

1.1 Ontario Hydro Steam Generator Experience

In July 1985, a paper was presented by the author at the 'Nuclear Power Plant Aging' conference. This paper has since been published in the conference proceedings/1/, and is appended to this report.

The paper briefly reviews the excellent reliability of Ontario Hydro's CANDU steam generators, and summarizes the results of analysis of failed tubes removed from the U-bend region of steam generators at Bruce A. In the majority of cases, crack initiation and propagation in these tubes has been caused by fatigue mechanisms/2,3/, although the initiation mechanism in one tube was found to be stress corrosion cracking/4/.

Table 1 summarizes salient data on all tube failures in the Bruce A steam generators. Of the 11 affected tubes, only in one case has a part through-wall crack been found by inspection. Also, circumferential through-wall cracks have only been observed at the 7th and 8th support plate locations. Figure 1 shows locations of all failed tubes.

An extensive review of literature on stress corrosion cracking and fatigue processes was made for the paper shown in Appendix 1 /5-14/. Based on this review and the results of failure analyses of tubes removed from Bruce A, a synergistic stress corrosion cracking/fatigue mechanism was proposed to account for initiation of U-bend failures in tubes exposed to high in-service mean stresses (see Appendix 1).

Generally experience with failures initiated by fatigue/stress corrosion cracking processes, suggests that unless corrective action is taken, failures will continue. In the case of steam generator tubes, where a large number of component parts are under similar operating conditions, the frequency of

failures can increase with time unless measures are taken to reduce contributory factors of stress, material susceptibility or aggressiveness of the environment.

To date, all tube failures in the U-bend region have occurred in inner steam generators (see Table 1), possibly as a result of increased heat transport flow through, and higher steaming rate. Some modifications have been made at Bruce A to equalize heat transport flow in the inner and outer boilers. Thus, the heat load and steaming rate in inner boilers has been reduced, whilst that in the outer boilers has increased/15/. Consequently, steam flow rates, and tube vibrational frequencies/amplitudes of tubes in the U-bend region of inner boilers may have been reduced. This may explain the absence of tube failures since these modifications were implemented (with reference to Table 1, the last tube failure occurred in September 1983).

1.2 External Experience with Steam Generator Tube Fatigue

Experience with similar fatigue-related failures has been limited to Once-Through steam generators at the Oconee and Rancho Seco plants/16/. Extensive analysis was undertaken to understand and prevent these failures/17-20/. Consequently, ameliorative measures were taken at Oconee and appear to have resulted in a cessation of fatigue failures.

Comparison of the results from Bruce A and Oconee is useful since tube material and, to a lesser extent, environment is quite similar for steam generators in both plants, and results of the Oconee investigation are well documented. Discussions were held with Babcock and Wilcox staff in order to compare the features of failure analyses of tubes removed from both plants. Whilst the cause of failures, namely fatigue, in both cases is a common feature, there are some key differences as described in Appendix 1.

A major difference is the role played by environment. In the case of Oconee failures, corrosion damage provided surface initiation sites, whereas for Bruce A minimal tube corrosion was found to be present at the initiation sites. The absence of such corrosion damage at Bruce A implies that, given approximately the same number of cycles to failure and similar material susceptibility to fatigue, then total operating tube stresses are higher at Bruce A.

1.3 Rationale and Objectives

The processes leading to crack initiation (described in Appendix 1, and discussed in Section 4), lead to the formation of dislocations within the tube wall and extrusions/intrusions on the tube surface.

Thus, careful examination of tubes without detectable cracks, removed from the critical region, may provide evidence of fatigue crack precursors described above. Unfortunately, in only one case has a sacrificial tube (# 55-10 from

Bruce A unit 3, steam generator 7) contained the region within the top support horizontal support plate, where cracks were observed in other tubes - see Figure 1.

This report describes results of examination of the sacrificial tube # 55-10 for crack fatigue precursors.

In order to interpret the results, for comparative purposes, a limited series of fatigue tests were performed on Inconel 600 (I600) tubing. Laboratory fatigue tests have been performed on samples of I600 tubes. Both these tubes tested in the laboratory and tubes removed from Bruce A steam generators have been examined using transmission and scanning electron microscopy.

The objective of the work reported here therefore, is to determine whether early fatigue damage is present on non-leaking tubes removed from the critical region within the Bruce A steam generator U-bends. This is intended to provide information in order to help assess the probability of further similar steam generator tube failures occurring at Bruce A.

2.0 PROCEDURE AND RESULTS

2.1 Fatigue Test Program.

Details of the test program are shown in Table 2. I600 tubes were tested in both the as-received condition, and following heat treatment at 600°C for 24 hours. This heat treatment was performed in order to duplicate effects of steam generator heat treatment during fabrication. Circumferentially-oriented notches of various geometries were machined on the outside surfaces of tubes, at locations corresponding to the tube midpoints. Grips were brazed onto both ends of the tubes for securing onto the test frame.

Mean tensile stresses ranging from 207-345 MPa were applied, with alternating stresses ranging from 69-214 MPa. These stresses are believed to be far higher than those acting on tubes in operating steam generators, in order that results could be obtained within a reasonable time. Test frequencies were between 5-10 hertz.

In some cases, failure occurred in the region of the grips. Tests were terminated once a crack became visible within the notch. In three samples, failure occurred close to the ends of the tubes associated with the grips, prior to the formation of a visible crack in the notch.

Following testing, notches were examined by both optical and scanning electron microscopy. Sample 2 provided the best evidence of fatigue damage and further detailed examinations were performed on this tube. Figure 2 shows extrusions/intrusions and cracks found on the surface of the notch root in sample 2. Figure 3a shows the presence of slip bands found on sample 2 in a through-wall cross section. The slip bands corresponding to the locations of surface intrusions/extrusions in Figure 2. Slip bands were also found in leaking tubes removed from steam generators as shown in Figure 3b.

Figures 4a and b show typical fracture surfaces on tested samples. These were generally similar to those observed on the crack surfaces on removed steam generator tubes; ie. faceted and transgranular, with striations present - see Appendix 1, Figure 4.

Finally, a radial-axial section was taken through the notch and in a region away from the notch in test sample #2, as shown in Figure 5. Transmission electron microscopy was performed on foils prepared from this section. As expected, dislocation density was found to be significantly higher in the region corresponding to the notch, as shown in Figures 6a-c.

2.2 Examination of Sacrificial Tube

The only sacrificial tube available including a portion from within the top horizontal support plate was tube #55-10 from Unit 3, steam generator 7 - see Figure 1. Figure 7 shows a sample of this tube with a region that had been in contact with the trefoil land. Locations of foils for transmission electron microscopy are also shown. These foils were taken in the radial axial orientation shown in Figure 5. Optical and electron microscopy of tube surfaces in the critical regions where cracks had been observed in failed tubes, failed to reveal any evidence of cracking or extrusions/intrusions similar to that observed on laboratory tested samples shown in Figure 2. However, given the rough surface condition of the land region, it is not surprising such evidence was not found.

Representative results of transmission electron microscopy of foils taken from the upper land region are shown in Figures 8a-d. Results of examinations of foils from regions >25 mm away from the land region, are shown in Figures 9a-c. These results show significantly higher dislocation densities in the region of the upper land where cracks had previously been observed in failed tubes, compared to other regions examined.

3.0 DISCUSSION

3.1 Analysis of Present Results

Results presented above show that observable differences in dislocation densities are present in the critical upper land region of the sacrificial tube when compared to other regions of the same tube. The upper land region corresponds to the location where cracks have been found in leaking tubes removed from the Bruce A steam generator.

Similar differences were also observed in laboratory fatigue-tested samples, between locations of high stress intensity (surfaces of notches) and unnotched or virgin samples of tubing. Extrusions/intrusions were also found on the notch surface of a laboratory fatigue tested sample. Similar surface damage was not found on the sacrificial tube. This may be due to the prior removal of a thin surface layer during etching for the purpose of residual stress measurements.

The relative differences in dislocation densities between the different regions is particularly important. On this basis these differences cannot reasonably be explained by their introduction during preparation of foil samples. Thus. these results would appear to indicate that upper land regions of the sacrificial tube had been exposed to (cyclic) stresses prior to the present examination.

Should further leaks occur in the upper U-bend region of Bruce A steam generators more sacrificial tubes should be removed containing the portion of the tube within the top horizontal support plate. Examination of these tubes will provide further information on dislocation densities and hence serve to support or negate the above conclusion.

I600 is a face-centered-cubic (fcc) substitutional solid solution. A review of literature on fatigue damage processes in fcc materials has been made/21-23/. Fatigue damage is generally divided into three stages, namely, (1) fatigue hardening in which dislocations are produced (where high stress amplitudes are present, softening has been observed in fcc materials), (2) microcrack nucleation, and (3) crack propagation ending in component failure.

Presently, there is only limited mechanistic understanding of the processes occurring in stage 1. These include dislocation generation, the arrangement of dislocations into cell boundaries within grains, and ultimately the formation of persistent slip bands. These slip bands can finally emerge at the surface, leading to the formation of intrusions/extrusions at the surface, and subsequent crack initiation at these sites. The formation of persistent slip bands is critical to the nucleation of a cracks in steam generator tubes at Bruce A where minimal corrosion damage has been observed at the initiation location.

Slip, i.e. the movement of atomic layers over each other, occurs during plastic deformation, when there is a resolved shear stress. It generally occurs in the most closely packed planes along the most closely packed directions. In the case of fcc materials such as I600 this corresponds to the {111} planes, in the <110> directions.

When slip occurs, the slipped plane consists of both slipped and unslipped regions. Between these two regions the lattice planes will be dislocated, giving rise to line defects or dislocations. Thus a dislocation forms a closed loop in the interior of the crystal or emerges at the surface.

During the major part of the fatigue life at normal temperatures (including those present in operating steam generators), dislocations are continuously being produced and annihilated by interactions with each other. Most of the hardening arising from dislocation generation appears to occur very early in the fatigue life, probably in the first few percent of total fatigue life. Also a microcrack may not form until more than 95% of the total tube life has been exhausted. Thus, in the present work, it is not possible to estimate the

proportion of the total fatigue life which has been expended in the sacrificial tube.

Experimental evidence of damage arising from low stress intensity fatigue such as that present in the Bruce A steam generators is mainly applicable to aluminum and copper alloys/21/. However, these results can be extrapolated to I600. In general it is found that for materials with high stacking fault energy such as aluminum, two distinct types of dislocation structure are found. Persistent slip bands are found connected with surface intrusions and extrusions, whilst veins or bands of dislocations, and dislocation loops are present in the bulk of the metal, or in the case of steam generator tubes, the tube wall. These types of dislocation structure apparently do not depend on the number of cycles.

For austenitic 18/8 stainless steels, no differences have been reported between the interior and near-surface structure, with widely spaced bands of dislocations on slip planes/21/. This is relevant to the present investigation since it was not possible to prepare samples of near-surface material, and it would be expected that the tube wall would contain dislocation densities similar to those present near the tube surface.

3.2 Available data on I600

Since evidence of fatigue crack precursors have been found in the sacrificial tube, and fatigue/stress corrosion cracking failures have occurred at Bruce A, it is useful to examine available fatigue data on I600 and similar materials, in order to determine the stresses required for such failures to occur. These stresses may then be compared to those believed to exist in service. This improved understanding of the factors responsible for in-service failures should allow for increased predictive ability, and determination of optimum strategies for remedial measures should further failures occur.

Laboratory data on fatigue of I600 is limited. The upper curve in Figure 10 shows the S-N relationship for laboratory tests performed in air at 1860 cycles per second, at 315°C, for a stress ratio (R) = -1 where R is the minimum stress/ maximum stress/24/. The lower curve is the estimated fatigue strength without the inhibiting effects of high frequency cycling/24/. Thus, based on this figure, the endurance or fatigue limit (alternating stress amplitude below which fatigue failure does not occur) is approximately 160 MPa in air. Note that the alternating stress amplitude is defined as one half of the range of any stress cycle.

S-N curves and data presented by Babcock and Wilcox at an EPRI workshop on corrosion fatigue/20/ is shown in Figure 11. Test environments include supersaturated steam, water, and air at 288°C, with R = 0. This data appears to show failure occurring in saturated steam at 10^7 cycles for an alternating stress amplitude of approximately 117 MPa.

A tube outer surface temperature of 270°C has been determined for the U-bend region/25/. Thus above data is in the applicable temperature regime, and the

data generated in supersaturated steam would be somewhat analogous to that present in the Bruce A steam generators.

Reviews of available data on fatigue/24,26,27/, and SCC/13,28,29/ crack propagation rates in I600 have been made. This data is not reported here since the processes leading to crack initiation are most important in relation to failures at Bruce A. Evidence from striation spacings (0.5-1 microns) and estimated operational cyclic frequency (~50 hertz), would suggest that once a detectable crack has initiated it may progress through-wall in a matter of hours. This implies that periodic inspection of steam generator tubes would be unlikely to detect incipient cracks.

In view of the paucity of data available on the fatigue behaviour of I600 in the CANDU environment, a limited fatigue testing program should be considered.

3.3 Tube Stresses in Bruce A Steam Generators

Recent analysis has shown that maximum alternating stress amplitudes of up to 90 MPa are possible in tubes in the critical region of Bruce A steam generator/30/. This figure is close to the fatigue threshold of 117 MPa quoted earlier.

Also, fatigue failures are known to occur at predominantly low cyclic stress amplitudes, well below those expected to cause failure, if the component is subjected to a high stress transient. There is no evidence that this may have occurred in Bruce A steam generators, however.

The failure analyses indicated that tensile mean stresses present during operation varied considerably. The presence of large shear lips on some tubes examined would indicate that high mean stresses were present on those tubes. However, the failure to observe a shear lip may not necessarily imply the absence of a high tensile mean stress during the early stages of fatigue crack initiation. Since it is unlikely that cyclic stress amplitudes vary significantly from tube to tube (as would be required to explain failures of tubes with varying tensile mean stress), it is likely that high mean stresses were present at the initiation location in all failed tubes.

There is no data available for I600 which accounts for the effect of mean stress. However, it is generally recognized that the curves of alternating stress amplitude versus number of cycles to failure will be lowered as mean stress is increased. Thus the alternating stress amplitude required for failure decreases with increasing mean stress.

Unfortunately, given the unreliability of estimated size of the shear lips, it is difficult (and may not be possible) to make an accurate determination of the magnitude of the operating mean stress from the size of the shear lips. However, assuming operating tube alternating stress amplitudes are as high as 90 MPa, relatively low mean stresses are required for tube failure.

Stresses may be categorized as both reaction and live load stresses. Reaction stresses are produced during the fabrication procedure possibly during assembly or stress relief of the main vessel closure weld. Live load stresses arise from the pressure difference across the tube, flow induced vibration and differential thermal expansion between the tube bundle and the supporting structure. Of these stress sources, a major component the stress arising from distortion during the stress relieving operation. Indentations found in the tubes at the seventh support plate location may have arisen during this procedure. It is possible therefore that the combined tensile mean stress acting on the tube during operation may be close to the material's yield strength.

Residual stresses measurements were made on the sacrificial tube examined in the present study/31/. Axial tensile stresses of up to 109 MPa were found in the land region. In regions away from the land, residual stresses of 39 and 75 MPa were measured in the axial and circumferential directions respectively.

Atomic Energy of Canada data on tube residual stresses has been summarized by E. Price/32/. Generally, for straight Incoloy 800 tubing in the unstress-relieved condition with a ground outside surface, residual stresses are compressive in the axial direction, with tensile stresses of between 50 to 300 MPa in the circumferential direction. Residual stresses in the U-bend region in the axial direction vary with circumferential location, with measured stresses as high as 500 MPa.

Residual stresses decrease with increasing distance from the tube outside surface, with maximum measured axial tensile stresses of 100 MPa at 0.1 mm below the surface. This observation is significant since it implies that high mean stresses present at the tube surface could provide the stress required for crack initiation, although as the crack progresses through-wall, the magnitude of mean stress decreases thus leading to a small observed shear lip on some tubes.

Some relaxation of residual stresses would occur during stress relief, reducing peak axial residual stresses in U-bent tubing from 500 MPa to approximately 200 MPa. Although tubes at the top support plate were not part of the U-bend, distortion arising from the stress relief operation may have produced similarly high residual stresses.

The lower measured value of residual stress in the sacrificial tube may have resulted from its location in the tube bundle. The sacrificial tube which is from a peripheral location (no peripheral tubes have failed to date), may not have been exposed to the level of distortion compared to that seen by other failed tubes.

However, the magnitudes of residual stresses referred to above, combined with additional tensile stresses present during steam generator operation could have resulted in tube failures given the high estimated operating alternating stress amplitudes of 90 MPa.

3.4 Prognosis and Possible Remedial Measures

The role of mean and residual stresses has been reviewed for both fatigue/33,34/ and SCC/35,36/ of I600. These reviews are mainly concerned with crack propagation. Generally it can be stated that the probability of crack initiation increases with increasing mean (including residual) and/or alternating stress.

Based on the present work, and limited understanding of operating tube stresses present in the Bruce A steam generators, it is not possible to develop a meaningful quantitative assessment of the probability of further tube failures in the large radius U-bend region.

Measurements of in-situ stresses and tube vibrational amplitudes and frequencies are planned/37/. For these results to improve our predictive capability, however, the feasibility of performing a limited program of fatigue testing should be evaluated. Such a program would be long-term and would be required to simulate superimposed mean and residual stresses and environments present at Bruce A.

The long-term prognosis is complicated by several conflicting factors. For example, assuming the initiation mechanism is predominantly fatigue, it is generally accepted that if failure has not occurred following approximately 10^8 to 10^9 cycles, then further failures would not be expected. Tubes at Bruce A failed after more than 10^{10} cycles, assuming tube vibrational frequencies of approximately 50 hertz. This provides additional support for the synergistic fatigue/SCC model proposed in Appendix 1.

The high number of cycles to failure also implies that the total of all stresses acting on failed tubes is close to the threshold required for failure. Assuming other tubes in the same critical location, for which failure has not yet occurred, incur similarly high stresses close to threshold, then any small reduction in the total stress level acting on these tubes, could play a significant role in preventing further failures. Fatigue crack precursors in the form of dislocations found in the sacrificial tube may not lead to crack initiation and propagation if such stress levels were reduced. Thus, modifications made to the steam generators referred to earlier (see section 1.0), may have resulted a small but significant reductions in alternating stress amplitudes.

Another important consideration in any assessment of the probability of further failures is the recent observation that aging of the tube material may occur with exposure to operating steam generator temperatures. There has been an increased incidence of primary side SCC in steam generators in Pressurized Water Reactors/38/, which may be attributed to this phenomenon. I600 tubing used in Bruce A steam generators was heat treated above 980°C, the temperature below which the material is known to exhibit considerably decreased resistance to SCC. However, the influence of subsequent aging at steam generator operating temperatures will have a negative implications (which cannot be quantified), for further failures.

The above factors which cannot presently be quantitatively assessed, do not allow for any reasonable determination of probability of further tube failures to be made.

In the event further tube failures should occur, however, few remedial measures with any practical value are available. Grinding of the surface layers containing microcracks and extrusions/intrusions, is known to increase fatigue life of components. Shot peening has been suggested as a method of sealing small surface cracks/39/. Both these measures would not be practically feasible to implement on tube outside surfaces where cracks have initiated. A high temperature stress-relief may have some beneficial effects in reducing dislocation densities in tubes where microcracks have not initiated, and reducing residual stress levels. Such a procedure has been developed to prevent SCC in the transition region where tubing is rolled into the tubesheet/40/. Utilization of this technique in the U-bend region however would be practically extremely difficult, and will require considerable development.

4.0 SUMMARY AND CONCLUSIONS

4.1 Based on a review of literature on fatigue and stress corrosion cracking processes and failure analyses of tubes removed from the Bruce A steam generators, a synergistic stress corrosion cracking/fatigue mechanism was proposed (at a recent conference on Nuclear Power Plant Aging) to account for crack initiation in tubes with high mean stresses.

4.2 A sacrificial steam generator tube (#55-10) removed from Bruce Unit 3, steam generator 7 has been examined using Scanning and Transmission Electron Microscopy. Samples of I600 tubes which were fatigue tested in the laboratory were also examined for comparative purposes.

4.3 Dislocation densities were found to be significantly higher just beneath the upper land region of the sacrificial tube, when compared to other locations in the same tube. This is the location where cracks had previously been found on leaking tubes.

4.4 An I600 tube which was fatigue tested in the laboratory showed a similar increase in dislocation density at a location of high stress intensity produced by a notch machined into the tube surface. Extrusions/intrusions similar to those found on the surface of the notch were not observed on the sacrificial tube possibly on account of deposits and prior surface etching of the tube.

4.5 Based on this limited evidence from one sacrificial tube, a possible explanation of the increased dislocation density is the presence of alternating stresses during operation, producing tube damage similar to that expected in fatigue processes. It is not possible to determine the extent of the damage, ie when crack initiation will occur.

4.6 Estimated maximum alternating stress is just below that required for fatigue failures in the absence of a tensile mean stress. Thus, given the presence of high tensile mean stresses, both fatigue failures, and the presence of increased dislocation density, are not unexpected.

4.7 Modifications made to the Bruce A steam generators may have lowered the stress amplitudes/frequencies of tubes in the critical U-bend region, and hence may account for the recent lack of tube failures.

4.8 Should further leaks occur in the upper U-bend region of Bruce A steam generators, sacrificial tubes containing the portion of the tube within the top horizontal support plate should be removed together with any leaking tubes, for further examination.

4.9 Further work is planned to determine tube stresses and vibrational behaviour in-situ. A program of limited laboratory fatigue tests should be considered. Some consideration should also be given to developing practical in-situ remedial measures to decrease the failure rate should further tube leaks occur.

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TABLE 1

SUMMARY OF STEAM GENERATOR TUBE FAILURES AT BRUCE A

Unit	SG	Tube #	Support Plate #	Type of Defect	Initiation Point (ID/OD)	Crack Depth	Crack Length (mm) (4)	Initiation Mechanism	Growth Mechanism	Removed for Analysis (X)	Operating Hours (5) (Date of Leak)
2	3	C53S13	7	Crack	-	TW(3)	-	-	-	-	2000 (77/12)
2	3	C56S11	7	Crack	-	TW	-	-	-	-	2000 (77/12)
2	3	C55S12	7	Crack	ID	0.8xTW	-	-	-	-	2000 (77/12)
2	6	C55S11	8(1)	Circ Crack	-	TW	-	-	-	-	8000 (79/10)
2	7	C53S12	8	Circ Crack	ID	TW	140°	SCC	Fatigue	X	16000 (79/12)
4	3	C57S10	7	Circ Crack	OD	TW	180°	Fatigue	Fatigue	X	30000 (83/3)
4	6	S13C10	TS-1	Pinhole	-	TW	-	-	-		23000 (82/05)
3	7	C56S10	7	Circ Crack	OD	TW	180°	Fatigue	Fatigue	X	38000 (83/07)
3	7	C54S11	7	Circ Crack	OD	TW	150°	Fatigue	Fatigue	X	38000 (83/07)
3	7	C51S15	7	Circ Crack	OD	TW	180°	Fatigue	Fatigue	X	39000 (83/09)
3	6	S16C10	TS(2)	Axial Crack	ID	TW	37 mm	SCC(6)	SCC(6)		32000 (82/09)

All defects found in hot legs of steam generators.

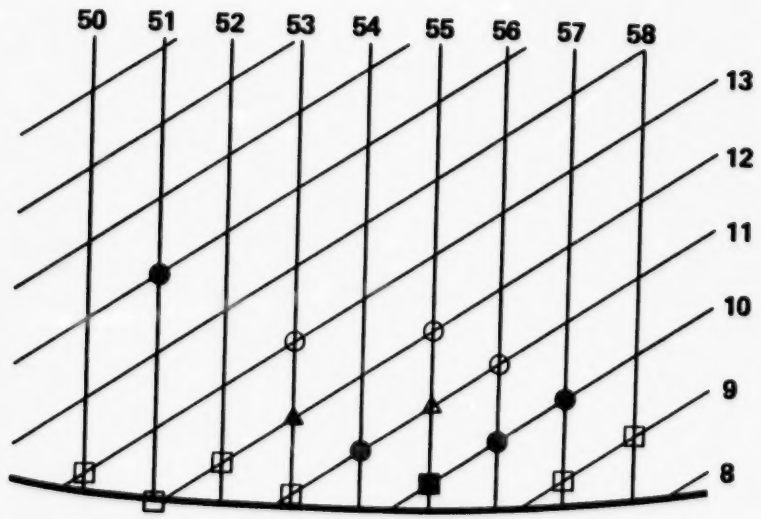
Legend:
(1) Support plate 8 = 40° scallop bar support
(2) TS = just above tube sheet
(3) TW = throughwall
(4) Crack length (mm) or circumferential extent on removal (degrees)
(5) Operating hours to leak based on 7000 hr/annum
(6) Most likely mechanism

TABLE 2

LABORATORY FATIGUE TESTING PROGRAMS

Sample #	Condition(1)	Notch Geometry	Mean Tensile Stress (MPa)	Alternating Tensile Stress (MPa)	Total Cycles
1	AR	1 mm dia 0.25 mm deep	345	138	4×10^5
2	HT	1 mm dia 0.10 mm deep	248	214	8×10^4
3	AR	Narrow 'V' slit 2.2 mm long 0.05 mm wide 0.1 mm deep	345	138	1.6×10^5
4	HT	Narrow 'V' slit 2.2 mm long 0.05 mm wide 0.1 mm deep	207	69	15.7×10^6
5	HT	Narrow 'V' slit 2.2 mm long 0.05 mm wide 0.1 mm deep	207	138	5×10^5
6	AR	Narrow 'V' slit 2.2 mm long 0.05 mm wide 0.1 mm deep	345	69	2.6×10^6

(1) AR - As Received
HT - Heat Treated (607°C for 24 h)



○ *Defect at 7th Support*

△ *Defect at 8th Support*

▲● *Tube Removed for Failure Analysis*

□ *Non-Defective Peripheral Tube*

■ *Sacrificial Tube for Present Analysis*

FIGURE 1

LOCATION OF DEFECTS IN HOT LEG, U-BEND REGION
OF BRUCE A STEAM GENERATORS

171686-RD

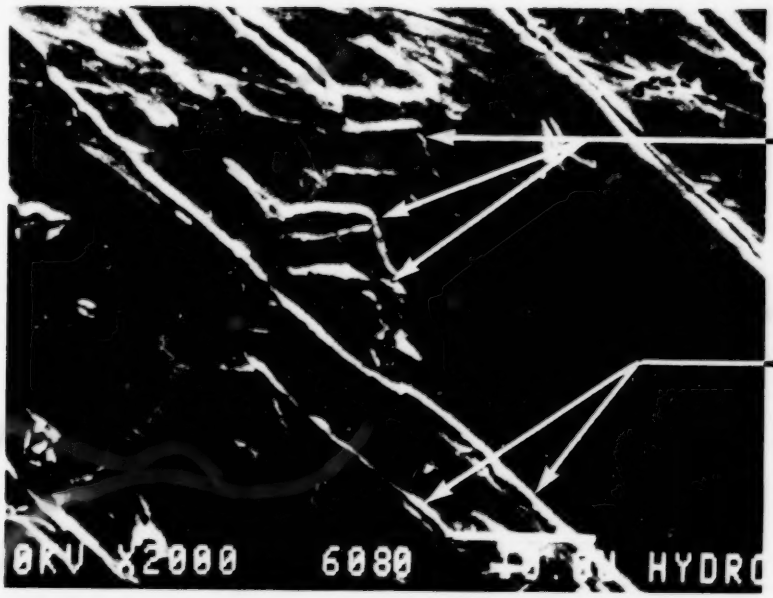


FIGURE 2

SURFACE FEATURES AT THE NOTCH REGION OF
LABORATORY FATIGUE TESTED SAMPLE (200x)

171687-RD

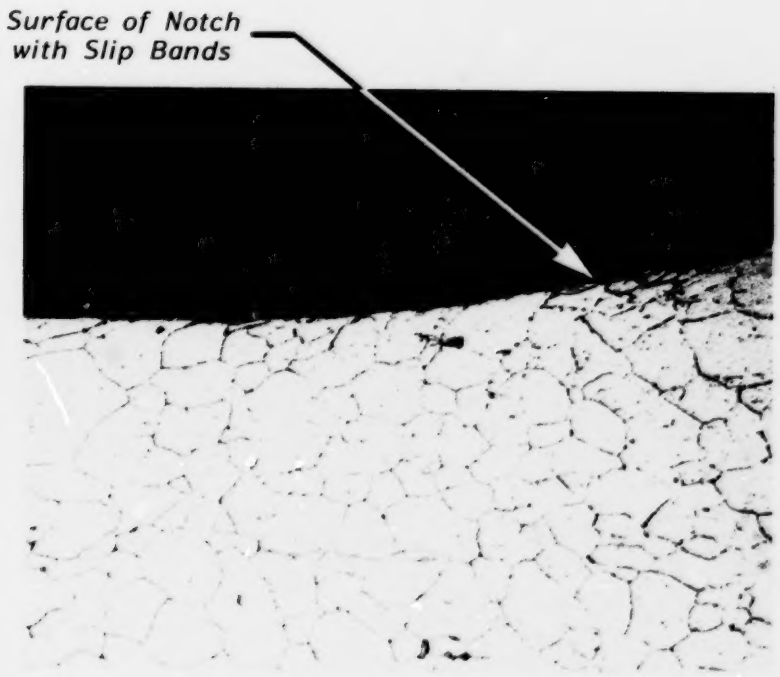


FIGURE 3a

THROUGH-WALL CROSS-SECTION AT SURFACE INTRUSIONS/EXTRUSIONS ON LABORATORY FATIGUE TESTED SAMPLE (400x)

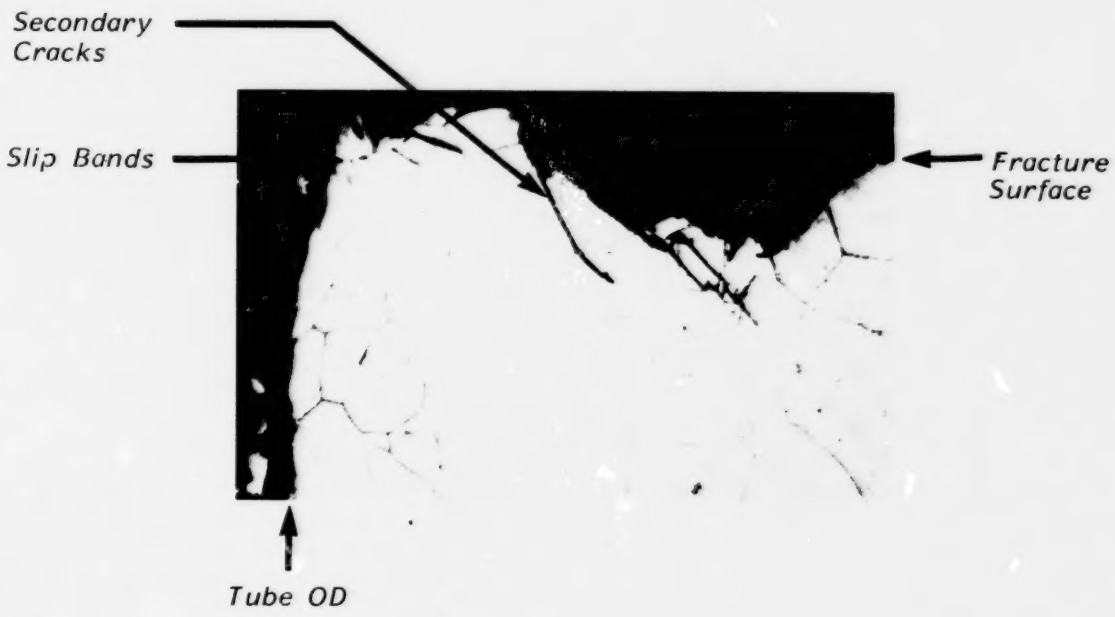


FIGURE 3b

CROSS-SECTION AT FRACTURE SURFACE OF LEAKING TUBE REMOVED FROM BRUCE A STEAM GENERATOR (400x)

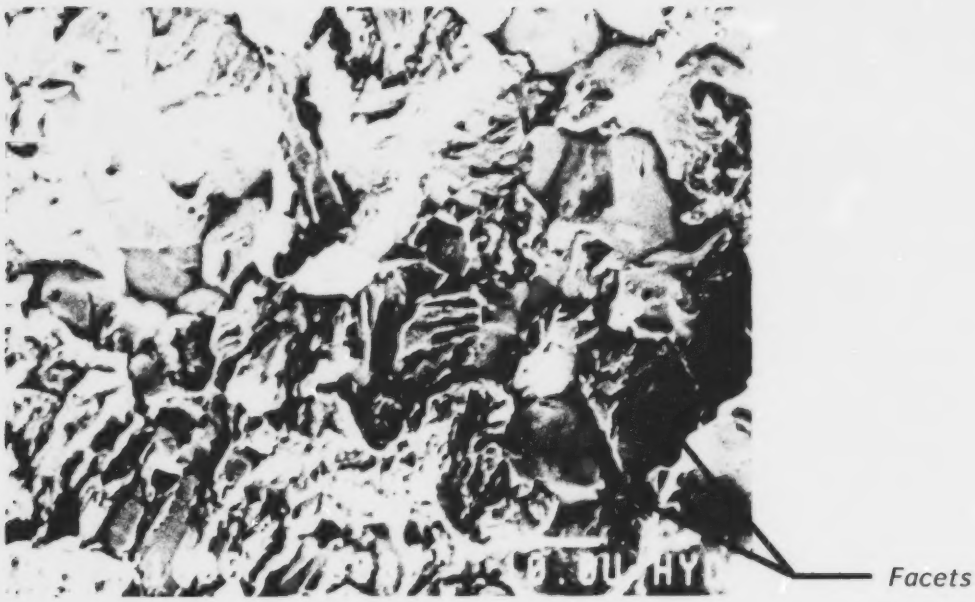


FIGURE 4a

SCANNING ELECTRON MICROGRAPH (100x)

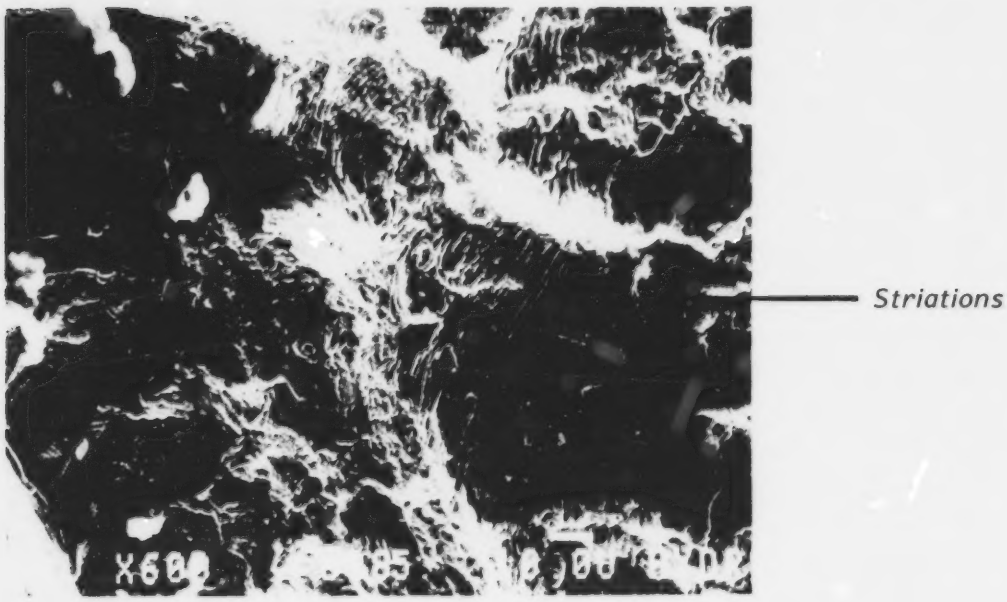


FIGURE 4b

SCANNING ELECTRON MICROGRAPH (600x)

TYPICAL FRACTURE SURFACES ON LABORATORY FATIGUE TESTED SAMPLES SHOWING FACETTING AND STRIATIONS

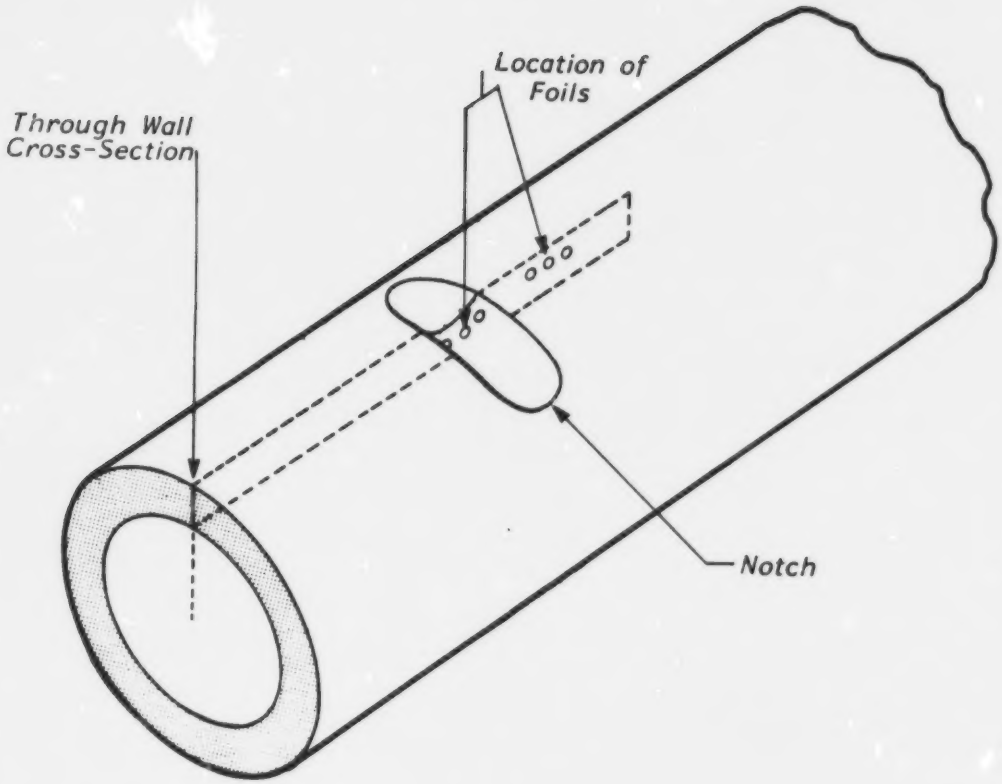


FIGURE 5

DIAGRAM SHOWING LOCATIONS OF THIN FOILS
IN LABORATORY FATIGUE TESTED SAMPLES

172637-RD

FIGURE 6a

FIGURE 6b

TRANSMISSION ELECTRON MICROGRAPHS OF REGION JUST BELOW SURFACE OF NOTCH IN LABORATORY FATIGUE TESTED SAMPLE, 50,000x

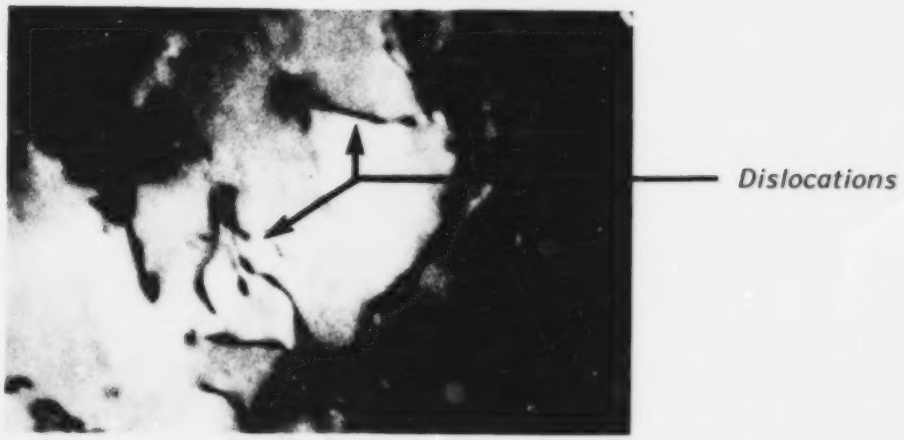


FIGURE 6c

TRANSMISSION ELECTRON MICROGRAPH OF UN-NOTCHED REGION IN LABORATORY FATIGUE TESTED SAMPLE, 50,000x

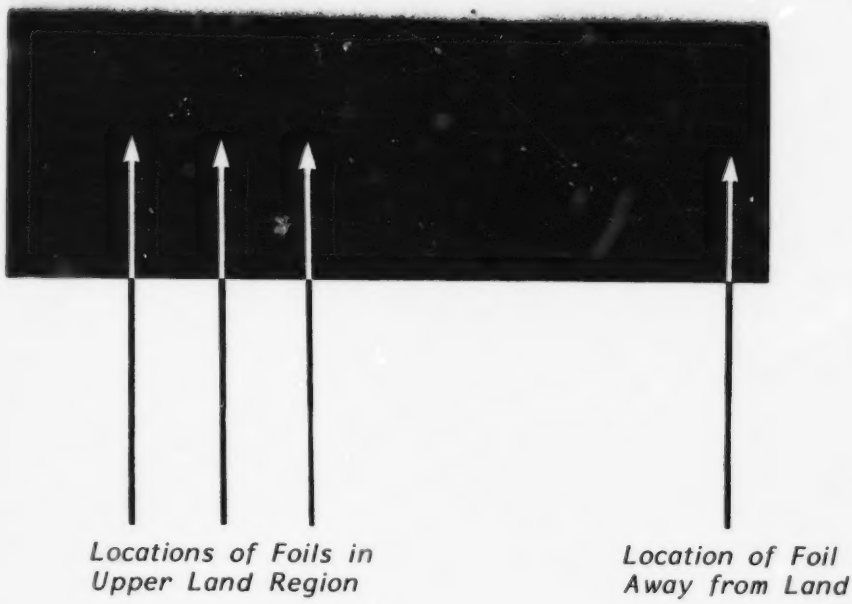


FIGURE 7

SURFACE APPEARANCE OF SACRIFICAL TUBE (55-10)
SHOWING LAND REGION AND LOCATION FOILS

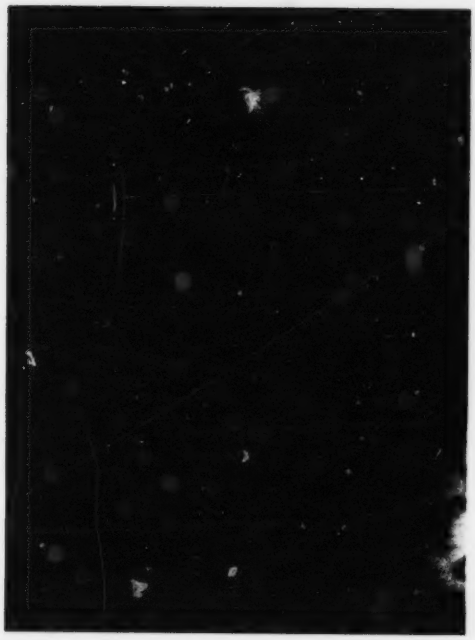


FIGURE 8a (50,000x)

FIGURE 8b (50,000x)

FIGURE 8c (50,000x)

FIGURE 8d (50,000x)

TRANSMISSION ELECTRON MICROGRAPHS OF FOILS TAKEN FROM UPPER LAND REGION OF SACRIFICIAL TUBE (55-10)

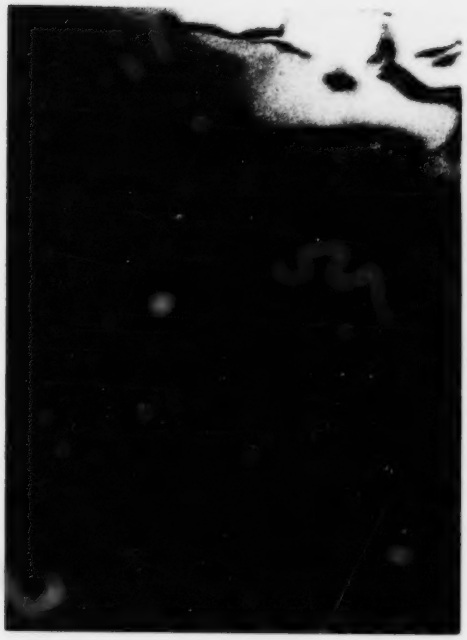


FIGURE 9a (50,000x)

FIGURE 9b (50,000x)

FIGURE 9c (50,000x)

FIGURE 9d (50,000x)

TRANSMISSION ELECTRON MICROGRAPHS OF FOILS TAKEN AT >25 mm AWAY FROM THE LAND REGIONS IN SACRIFICIAL TUBE (55-10)

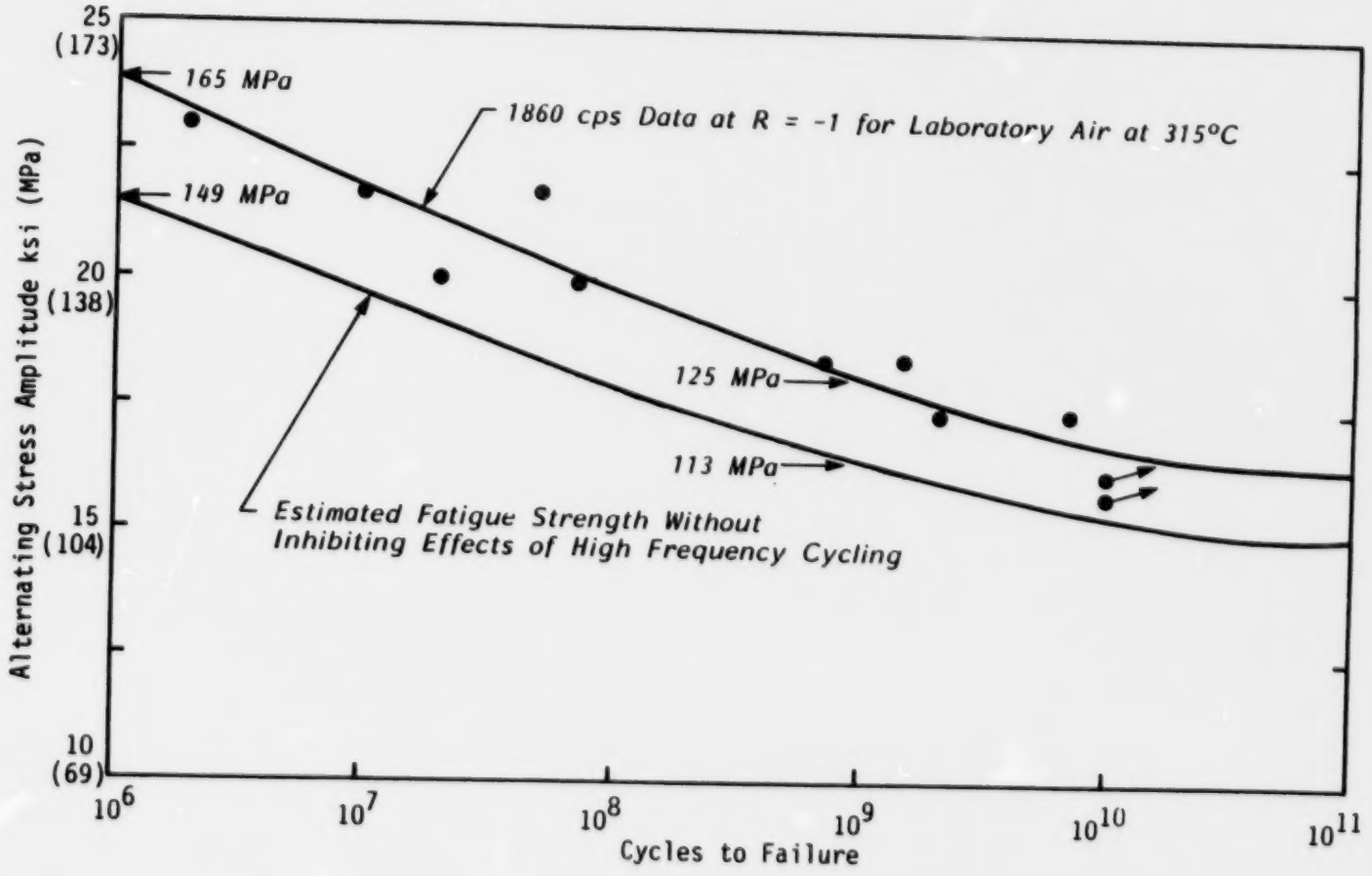


FIGURE 10
HIGH-CYCLE FATIGUE RESULTS FOR INCONEL 600 (FROM REFERENCE 24)

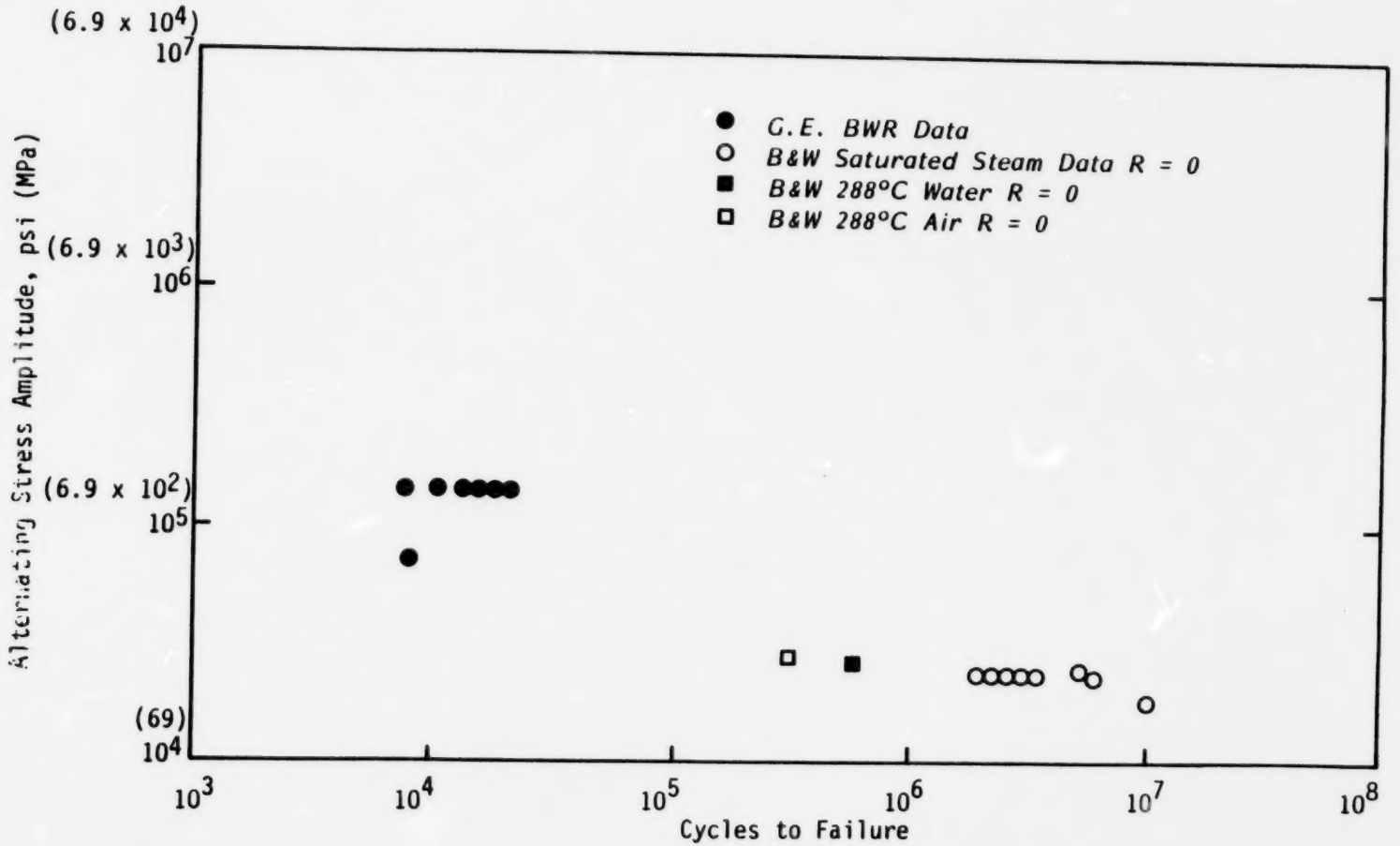


FIGURE 11

BABCOCK & WILCOX UNPUBLISHED FATIGUE DATA FOR INCONEL 600 (FROM REFERENCE 20)

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OPERATING EXPERIENCE AND LABORATORY STUDIES WITH FATIGUE AND STRESS CORROSION CRACKING OF INCONEL 600 STEAM GENERATOR TUBES AT ONTARIO HYDRO

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ABSTRACT

Ontario Hydro has experienced a small number of Inconel 600 tube leaks in U-tube steam generators in CANDU (Canadian Deuterium Uranium) operating reactors at the 4-unit Bruce A plant. Examination of tubes removed for failure analysis has shown that the leaks are caused by circumferential cracks which initiated predominantly at the tube outside surface adjacent to the top support plate. In the majority of cases, crack initiation and propagation have been caused by fatigue mechanisms. Corrosive attack was minimal on the tube surfaces, and therefore corrosion mechanisms were generally not implicated in the failures. However, a synergistic stress corrosion cracking/fatigue mechanism is thought to have initiated cracks in those tubes exposed to high mean stresses. Sources of the alternating and mean stresses are being investigated.

ONTARIO HYDRO operates fourteen CANDU (Canadian Deuterium Uranium) reactors with a combined net capacity of 8233 MW(e). An additional seven CANDU reactors with a net capacity of 5626 MW(e) are presently under construction. Information on Ontario Hydro's major CANDU plants is shown in Table 1. Generally steam generators (SG) are of similar design to U-tube SGs employed in pressurized water reactors (PWR), namely vertical U-tube with steam separation equipment housed in the SG head. SGs at the 4-unit Bruce A nuclear generating station are unique, with eight SGs/unit, connected in banks of four to a common steam drum, which contains the steam separation equipment as shown in Figure 1.

SG tube corrosion has had a considerable impact on the reliability of both U-tube SGs and Once-Through SGs (OTSG) in PWRs. Through-wall tube corrosion results in leakage of radioactive primary water into the secondary feed-water, thus providing a route to the external environment for radioactive contaminants.

Table 1

Data on Ontario Hydro CANDU Nuclear Plants(1)

Station	# Units	Net Capacity MW(e)/unit	#SGs/unit	% UNCAP(2) Total	% UNCAP(3) SG
Pickering A	4	515	12	23.16	0.3
Pickering B	4	516	12	13.82	0.2
Bruce A	4	754	8	13.00	1.7
Bruce B	4	795	8	14.07	0.0
Darlington A	4	880	4	under construction	

(1) NPD plant not included - Net Capacity 22 MW(e).
(2) Total Station % Incapability (4) (From in-service to March 1985).
(3) Station % Incapability due to steam generators (from in service to December 1984).
(4) Incapability is defined as production losses associated with the units' equipment and systems, and includes all causes.

Common tube failure mechanisms have included stress corrosion cracking (SCC), wastage and pitting corrosion. To date, tube failures arising from fatigue mechanisms have not been recorded in PWR U-tube SGs. Fatigue processes have, however, been responsible for circumferentially-orientated cracks in OTSGs at regions close to the upper tubesheet and top support plate. These have been the subject of extensive investigation (1,2,3).

SGs in Ontario Hydro's CANDU operating plants have experienced negligible tube corrosion damage. Tubes removed from the sludge pile region just above the tubesheet at both Pickering A and Bruce A have shown no evidence of pitting corrosion or wastage. Similarly, minimal general tube corrosion damage has been found in the U-bend region at Bruce A. The excellent performance of SG tubes is reflected in the relatively small contribution of SGs to total station incapability as shown in Table 1.

To date, tube leaks resulting from fatigue or SCC have only occurred in Bruce A SGs. Each Bruce A unit has eight SGs, with 4200 Inconel 600 tubes in each. By the end of 1984 approximately 8×10^9 tube operating hours had

been recorded in SGs at Bruce A. During this period, a total of eleven tube defects had been found, nine of which resulted in tube leaks. Five of these leaking tubes have been removed for failure analysis, the results of which are presented below. Ontario Hydro continues to investigate the tube failures at Bruce A primarily to address questions related to the cause of the failures, the probability and consequences of further failures, and the possibility of practical preventative measures being developed to minimize further plant outages resulting from tube failures.

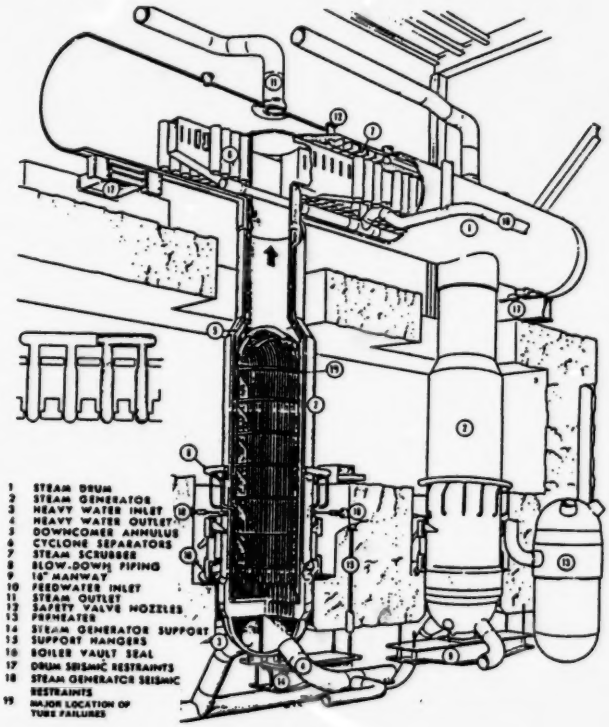

Fig. 1 Bruce A Steam Generator

FAILURE ANALYSIS OF REMOVED TUBES

Tubes removed from SGs at Bruce A have been subjected to metallurgical, chemical, and stress analyses. Most defects have been found in a very localized region within the SG tube bundle, at the top horizontal support plate, in the region of the large radius U-bends, as shown in Figure 1. Failures generally resulted from cracks orientated in the tube circumferential direction, initiating from the tube outside surface (OD), as shown in Figure 2. In one tube, however, the crack was found to initiate from the inside surface (ID). Minor fretting damage was observed at the initiation location in some failed tubes. Fretting was not judged to be a prerequisite for crack initiation.

Analysis of deposits present on some tubes within the top horizontal support plate showed relatively high levels of silicates and sulphates to be present. These deposits may have contributed to reducing the clearance between the tubes and support plates, although no evidence of tube corrosion was found as a result of aggressive environments created within the tube-tube support crevice. The condition of the tube OD was found to be free of any degradation normally associated with corrosion processes, both at the initiation location, and in other locations beneath deposits on the tubes as shown in Figure 3. Deposits were generally absent at the precise location of initiation as shown in Figure 3, indicating that the tubes were in continual contact with support plates during operation, thus providing a stress concentration effect.

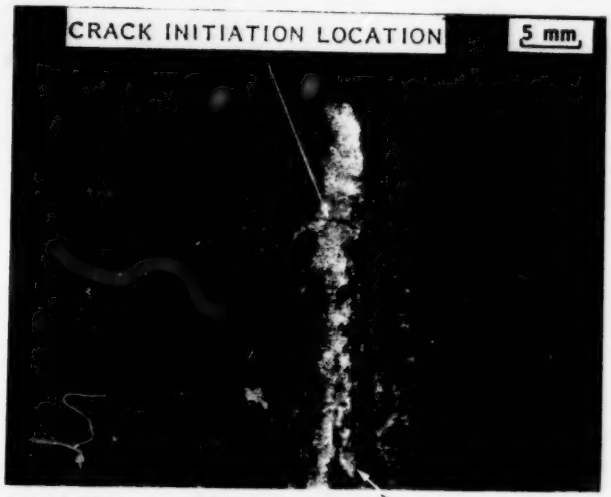

Fig. 2 Circumferential crack showing location of support plate land.

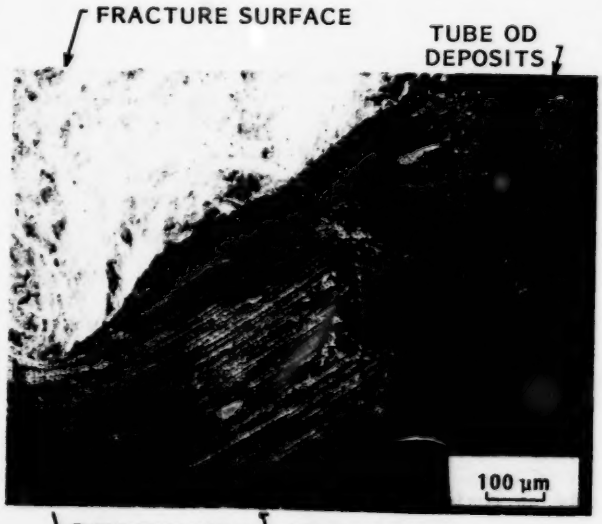

Fig. 3 Crack initiation location.

Crack surfaces were generally found to be facetted and transgranular, with occasional evidence of striations which point to fatigue processes involving cyclic crack advance, as shown in Figures 4a and b. The presence of facetting on fracture surfaces is indicative of slow crack growth generally attributable to stage 1 fatigue or SCC processes.

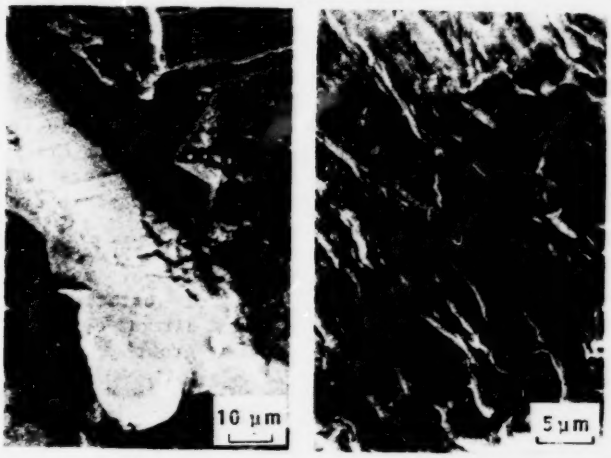

Fig. 4 Typical fracture surface showing (a) facets and (b) striations

The mechanism of crack initiation cannot be directly ascertained from the fracture surface, but rather implied from general features at the initiation location. Some evidence of multiple cracks indicative of a SCC mechanism was found at the crack initiation location on one tube in which the crack initiated from the ID, as shown in Figure 5. Cracks were generally singular and unique in other tubes in which cracking initiated from the OD.

Fig. 5 Through wall cross section at tube inside surface showing intergranular attack.

Examination of fracture surfaces showed the crack growth path to be irregular. Cross-sections through the tube walls at the initiation location revealed axial components to the crack growth directions, as shown in Figure 6. The presence of an axial component at the initiation location shown in Figure 6b implies the presence of a torsional stress component acting on the tube during operation. Furthermore, the presence of shear lips (see Figure 6a) indicates the presence of a significant tube mean stress, and a correspondingly high R value (minimum stress/maximum stress). The different sizes and locations of shear lips shown in Figure 6, suggest that the nature and magnitude of the mean stress varied considerably in these tubes.

As previously stated, tube fatigue failures have occurred in OTSGs. Those at the Oconee 1 plant have been extensively investigated (1,2). Tubes removed from SGs at the Oconee plant showed deposits, similar to those found on the Bruce A tubes, to be present. Also, there was considerable corrosion damage clearly observable on the tube OD surfaces, which probably acted as initiation points for fatigue. Since OD corrosion damage was not observed on the Bruce A tubes, and evidence for both fatigue and SCC mechanisms has been found, it is useful to examine the mechanisms of crack initiation and growth in fatigue and SCC processes.

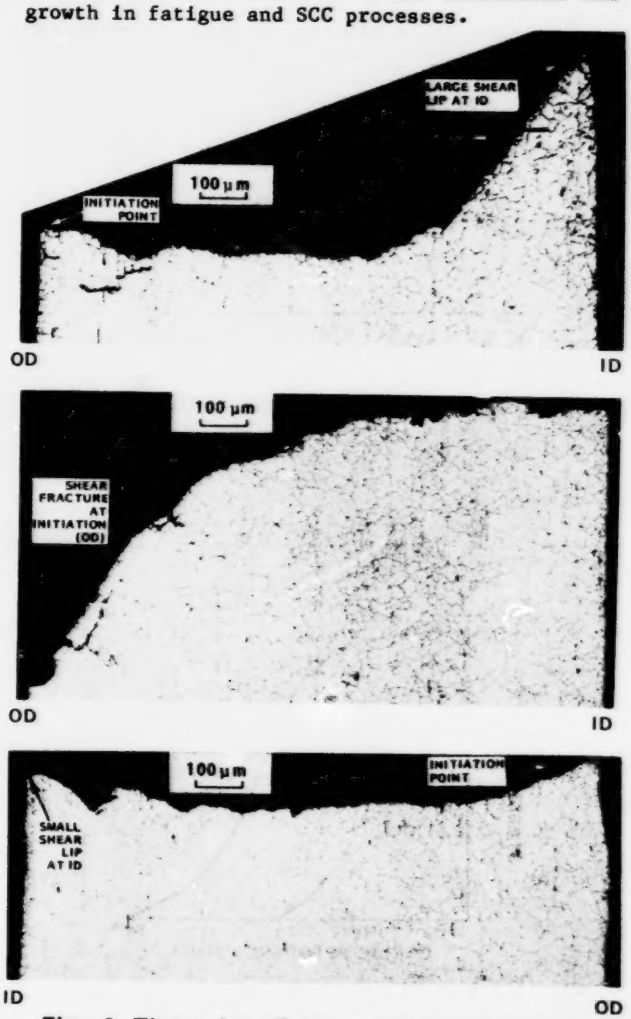

Fig. 6 Through wall cross sections of 3 tubes at initiation location.

In general fatigue is found to be a three-stage process with respect to crack growth rate as a function of the stress intensity

range, ΔK, as shown in Figure 7. In stage 1, crack growth rates are generally less than 10^{-9} m/cycle, thus approaching the order of an atomic spacing which is approximately 3 x 10^{-10} m for Inconel 600. The processes leading to crack nucleation which occur prior to Stage 1 include dislocation generation, arrangement of dislocations into cell boundaries within grains, and the formation of persistent slip bands. These slip bands can finally emerge at the surface, leading to the formation of intrusions/extrusions with subsequent crack initiation at these sites. These mechanisms probably played a leading role in the nucleation of cracks in Bruce A SG tubes, since OD corrosion damage was not observed.

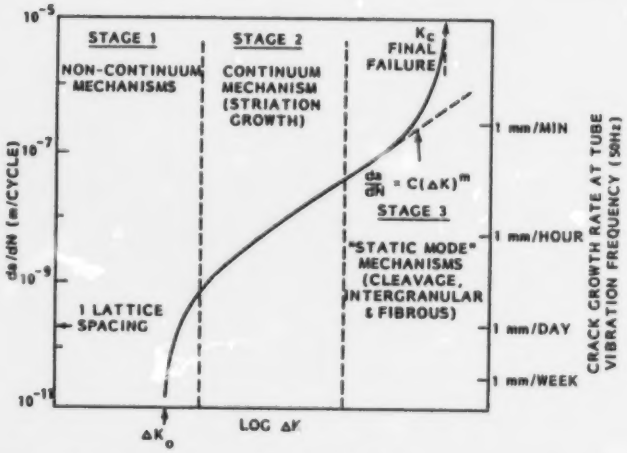

Fig. 7 Schematic variation of fatigue crack growth rate (da/dN) with stress intensity range (Δk).

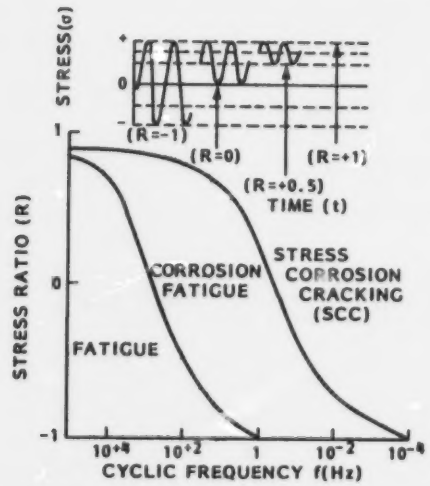

Fig. 8 - Relationship between SCC, corrosion fatigue and fatigue with stress ratio (R) and cyclic frequency

In both crack initiation and Stage 1, the synergistic effects of SCC and fatigue are important, particularly at high levels of the stress ratio (R), as shown in Figure 8 in which R is plotted schematically as a function of cyclic frequency (4). Mechanisms of SCC initiation are similar to those of corrosion fatigue, particularly in the processes of slip band formation, and their emergence at the surface followed by slip dissolution. Also, SCC can occur in the absence of general corrosive attack. The presence of a high tensile mean stress in some of the failed Bruce A tubes, may indicate that SCC mechanisms or synergistic SCC/fatigue mechanisms are responsible for crack initiation. In the tubes with lower operating mean stresses, fatigue initiation mechanisms are believed to be predominant.

Despite the possibility of synergistic SCC/fatigue mechanisms being present in the initiation phase, the presence of striations on the fracture surfaces provides direct evidence of the mechanism of crack growth, namely fatigue.

SUMMARY AND CONCLUSIONS

SGs in Ontario Hydro's operating CANDU reactors have demonstrated excellent reliability with negligible tube leaks arising from corrosion processes following more than 100 unit years of operation.

Tube leaks have occurred in the U-bend region of SGs at the Bruce A plant. Tubes removed for analysis showed the leaks were due to circumferentially-orientated cracks, initiating predominantly from the tube OD. Fatigue mechanisms have been identified as the major cause of crack initiation and growth.

A synergistic SCC/fatigue mechanism is believed to be responsible for crack initiation in tubes exposed to a high mean stress. Mean stress magnitudes appear to vary significantly between failed tubes.

Investigations into the cause of these tube failures continue. Residual stresses present on the removed tubes and in-situ tube operating stresses are to be determined.

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